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CONSIDERATION OF
AUXILIARY JET PROPULSION FOR ASSISTING TAKE-OFF

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CONSIDERATION OF AUXILIARY JET PROPULSION FOR ASSISTING TAKE-OFF

By L. Richard Turner

SUMMARY

The problem of assisting the take-off of an airplane by means of auxiliary jet propulsion has been analyzed and a simple method developed for determining the jet thrust and the weight of jet fuel required to provide a desired reduction in take-off distance or a desired increase in pay load or fuel load for a fixed take-off distance. The weight of a jet motor and the auxiliary equipment cannot, at present, be accurately predicted. Approximate estimates indicate, however, that the total weight will be sufficiently small, as compared with the weight of an internal-combustion engine and propeller required for the same improvement in take-off, that serious consideration should be given to this method of assisting the take-off.

INTRODUCTION

The problem of assisting the take-off of an airplane is old. As early as 1842, Henson attempted to use a catapult to launch a glider. This type of device has been highly developed for the launching of military airplanes, mail planes, and gliders (references 1 and 2).

The accelerator, or towing-type, take-off aid was used by the Wright brothers in their early flights. It has been used extensively to launch gliders and has been developed for airplanes by the Royal Air Force at Farnborough by the use of a compressed-air-driven motor and a towing cable. (See references 1 and 2.) Land-based accelerators running on rails or runways have been suggested (references 2 and 3) but apparently have not been built. In another proposed system, the force required for an accelerated take-off is supplied by a flywheel, which is set in motion by a small engine and which pulls a cable over a conical drum of increasing radius. (See reference 3.) Pröll (reference 4) has suggested towing one airplane with another, but this system has not been used except for towing target gliders.

Fueling in the air has been successfully developed and used for refueling during endurance tests and as a take-off aid. It is of especial value for long-range flights because it enables an airplane to take off with a lower wing loading and a lower power loading than those that apply in flight. Rough weather, however, interferes with its operation. (See references 1 and 2.)

The British firm of Short Bros. has built and successfully operated the Short-Mayo composite aircraft. The main advantage of this scheme is that it enables the airplane to take off with high wing and power loading and to climb quickly to the cruising altitude. (See references 1 and 2.)

Pröll has suggested (reference 3) that the energy of the engine be accumulated during the warm-up period as rotational energy in a heavy flywheel and that it be released to the propeller through a variable gear during the take-off. The weight of the device would be objectionable.

The use of a jet of water, projected to the rear by a gas pump, has also been suggested by Pröll as a take-off aid (reference 3). The weight of water required would be excessive because of the low jet velocity proposed.

Ley (reference 5) reports that auxiliary jet propulsion has been experimentally used by the Junkers plant at Dessau as a take-off aid for a seaplane of the Bremen type, weighing slightly more than two tons. The rockets used were "the largest type of powder rockets known." The results were officially described as "satisfactory and encouraging" although no data were published.

Rockets have been used on several occasions to launch and fly model airplanes and at least two partly successful rocket-powered flights have been made with piloted gliders. The gliders were launched with catapults. (See reference 6.)

Jet propulsion has been investigated by several groups in Europe and America. The experiments have been partly successful but many practical problems remain to be solved.

There are two main types of jet motors. The first type uses atmospheric air. Analyses by Buckingham (reference 7) and Oestrich (reference 8) give fuel consumptions that are never less than twice that of an internal-combustion engine and propeller producing the same thrust at airplane speeds as high as 350 miles

per hour. In addition, the weight of the required compressors would be at least as great as that of the internal-combustion engine even at this high speed.

The second type of jet motor uses an explosive fuel or a concentrated oxidant, which is carried by the airplane. For this type, it is convenient to consider the consumption of both fuel and oxidant as fuel consumption. As compared with that of an internal-combustion engine and propeller, the fuel consumption is very high but the weight of the motor would be very much lower per pound of thrust.

Attempts have been made to augment the thrust of jet motors by entraining atmospheric air in order to increase the rearward discharge of momentum. (See references 9 and 10.) The values of thrust increase achieved are insufficient to make jet propulsion practicable for sustained flight but might be of value for some special use of jet propulsion in which economy is not the principal consideration.

This report presents a study of the possibilities of jet propulsion as a take-off aid for reducing take-off distance with a given pay load or for increasing pay load with a given take-off distance.

ANALYSIS

The take-off distance will be considered as a ground run and a flight distance to clear an obstacle of height h . In this analysis, it will be assumed that, in still air, the unaided ground run and the flight distance to clear an obstacle are known for the normal loading and that the take-off velocity, V_t , and the mean velocity in flight, V_a , from the take-off to the point where the required altitude is reached are also known. The mean effective excess thrust, defined in each case by the known distances and velocities, will be assumed to be constant. It can be shown that the error due to the assumption of constant excess thrust in the reduced ground runs with constant added thrust is small and conservative, in that the predicted reductions in the ground run are smaller than those based on the actual variable value of excess thrust. For the flight portion of the take-off, the transition phase will be neglected because this neglect was shown by Wetmore (reference 11) to introduce only a small error in the calculated distance. The inclination of the flight path will also be neglected.

Reduction of the ground run by means of auxiliary jet propulsion. - With a constant effective excess thrust, the ground run is given by

$$s_o = \frac{V_t^2 W}{2gT_o} \quad (1)$$

where s_o is the unaided ground run, feet.

W gross weight, pounds.

V_t take-off velocity, feet per second.

T_o mean effective excess thrust, pounds.

With a constant added jet thrust, T_J , the new reduced ground run, s_o' , is given by

$$s_o' = (V_t^2 W) / [2g (T_o + T_J)] \quad (2)$$

from which

$$\left. \begin{aligned} \Delta s_o / s_o &= T_J / (T_o + T_J) \\ \text{or } T_J / T_o &= \Delta s_o / (s_o - \Delta s_o) \end{aligned} \right\} \quad (3)$$

where Δs_o is the reduction of the ground run.

If v is the relative velocity in feet per second of the jet of an auxiliary jet-propulsion device, the thrust is

$$T_J = \frac{v}{g} \frac{dw}{dt} = r \frac{dw}{dt} \quad (4)$$

where w is the weight of fluid discharged, pounds.

t time, seconds.

r reaction in pounds per pound of fuel per second.

Since both fuel and oxidant are carried by the airplane, it is convenient to consider the total weight of fluid as the weight of fuel.

The time for the reduced ground run is given by

$$t_o' = \frac{Ks_o'}{V_t} = \frac{KV_t W}{2g(T_o + T_J)} \quad (5)$$

where the value of the coefficient K for the case of constant excess thrust is 2. Since the excess thrust is not constant, the value of K is somewhat different from 2. Hartman (reference 12) gives an empirical value of 1.95, which will be used in the computations in this paper.

The rate of discharge of the jet was assumed to be constant, and the weight of fuel is therefore given from equations (3), (4), and (5) by

$$w_o = t_o' \frac{dw}{dt} = \frac{KV_t W}{2gr} \frac{\Delta s_o}{s_o} \quad (6)$$

and

$$\frac{dw}{dt} = \frac{T_o}{r} \frac{\Delta s_o}{s_o - \Delta s_o} = \frac{V_t^2 W}{2grs_o} \frac{\Delta s_o}{s_o - \Delta s_o} \quad (7)$$

The weight of fuel, w_o , required to reduce the ground run (equation (6)) is plotted using the experimental reactions for four different fuels (table I, fuels 1 to 4) in percentages of the gross weight of the airplane in figure 1(a) for a take-off velocity of 70 miles per hour and in figure 1(b) for a take-off velocity of 80 miles per hour. The total weight of fuel and the rate of fuel consumption are also shown for the 4,200-pound airplane. The unaided ground run of the assumed airplane was taken to be 500 feet in the calculation of the rate of fuel consumption.

In the case of take-off against a wind, it is merely necessary to substitute $V_t - V_w$ for V_t and s_w for s_o in equations (6) and (7) to determine the performance,

where V_w is the wind velocity, feet per second.

s_w unaided take-off distance against a wind.

The value of s_w may be conveniently found from figure 11 of reference 13.

There will now be analyzed the condition in which the jet is turned on when the airplane attains a velocity mV_t where m is an arbitrary parameter between 0 and 1. If a constant excess thrust of T_0 up to this point and a thrust of $T_0 + T_J$ from there on are assumed,

$$s_m = \frac{m^2 V_t^2 W}{2gT_0} = s_0 m^2 \quad (8)$$

where s_m is the distance traveled by the time the velocity mV_t is attained; from this point on, the distance is given by

$$s_0' - s_m' = \frac{V_t^2 W}{2g(T_0 + T_J)} (1 - m^2) \quad (9)$$

where s_m' is the reduced run to the point where V would equal mV_t had the jet been in operation from the start of the take-off. The total distance, s' , is then

$$s' = s_m + (s_0' - s_m') = \frac{V_t^2 W}{2g} \left(\frac{m^2}{T_0} + \frac{1 - m^2}{T_0 + T_J} \right)$$

and the fractional reduction in the ground run, $\Delta s_0/s_0$ is given by

$$\frac{\Delta s_0}{s_0} = 1 - \frac{s'}{s_0} = (1 - m^2) \frac{T_J}{T_0 + T_J} \quad (10)$$

The time during which the fuel was burned is

$$\begin{aligned} t_0' &= K \left(\frac{s_0'}{V_t} - \frac{s_m'}{mV_t} \right) \\ &= \frac{KV_t W (1 - m)}{2g(T_0 + T_J)} \end{aligned} \quad (11)$$

As in the case of equation (3), $w_0 = t_0' \frac{dw}{dt} = t_0' \frac{T_J}{r}$,

$$w_0 = \frac{KV_t W (1 - m)}{2gr} \frac{T_J}{T_0 + T_J} \quad (12)$$

or, from equations (10) and (12),

$$w_0 = \frac{KV_t W}{2gr} \frac{\Delta s_0}{s_0(1+m)} \quad (13)$$

Solving equation (10) for m gives

$$m = \left(1 - \frac{T_0 + T_J}{T_J} \frac{\Delta s_0}{s_0} \right)^{1/2} \quad (14)$$

The substitution of this solution for m in equation (12) or (13) gives w_0 in terms of T_J/T_0 and $\Delta s_0/s_0$.

Figure 2(a) shows the weight of gasoline and oxygen required to obtain a desired reduction in the ground run for various values of m and T_J/T_0 at an assumed take-off velocity of 70 miles per hour. In figure 2(b), the weight of fuel is plotted for a take-off velocity of 80 miles per hour.

Reduction of the length of the air-borne portion of the take-off by means of auxiliary jet propulsion. - The reduction in the flight distance to clear an obstacle of height h during the take-off will now be considered. It will be assumed that the airplane velocity during this phase is practically constant and that it has an average value of V_2 . The transition phase will be neglected because its neglect has been shown by Wetmore (reference 11) to have only a small effect on the calculated distance for normal take-offs. The normal velocity of climb, V_0 , is given by

$$V_0 = T_2 V_2 / W$$

where T_2 is the normal excess thrust. With an added thrust T_J

$$\left. \begin{aligned} V_0 + \Delta V_0 &= (T_2 + T_J) V_2 / W \\ \Delta V_0 &= T_J V_2 / W \end{aligned} \right\} \quad (15)$$

whence

The length of the unaided flight path, s_2 , to clear an obstacle of height h is

$$s_2 = \frac{h}{V_0} V_2 = \frac{hW}{T_2} \quad (16)$$

and with an added thrust, T_J , the reduced distance, s_2' , is given by

$$s_2' = hV_2/(V_0 + \Delta V_0) \quad (17)$$

from which

$$\frac{s_2'}{s_2} = \frac{V_0}{V_0 + \Delta V_0} = \frac{1}{1 + \frac{T_J s_2}{hW}} \quad (18)$$

Since $\frac{dw}{dt} = \frac{T_J}{r}$ (equation (4)), from equation (18)

$$\frac{dw}{dt} = \frac{s_2 - s_2'}{s_2} \frac{hW}{s_2 r} = \frac{hW}{s_2 r} \frac{\Delta s_2}{s_2} \quad (19)$$

The time, t_2' , for the aided climb is given by

$$t_2' = s_2'/V_2$$

From equation (19), the weight of fuel for the aided climb is

$$w_2 = t_2' \frac{dw}{dt} = \frac{hW}{V_2 r} \frac{\Delta s_2}{s_2} \quad (20)$$

Figure 3 shows w_2/W plotted against $\Delta s_2/s_2$ for four experimental jet fuels for mean take-off velocities of 70 and 30 miles per hour for a height h of 50 feet. The weight of fuel is also shown for two airplanes having gross weights of 4,200 and 42,000 pounds.

Reduction in total take-off distance by means of auxiliary jet propulsion. - The calculation of the reduction in total take-off distance will be made for the condition in which it is considered that the jet-propulsion device is turned on to provide an additional thrust, T_J , when the airplane attains a ground velocity of mV_t and continues to provide the same additional thrust throughout the rest of the take-off.

From equations (1), (10), and (18),

$$\Delta s_0 = (1 - m^2) \frac{T_J}{T_0 + T_J} s_0$$

$$\Delta s_2 = \frac{\frac{T_J s_2}{Wh} + T_J}{s_2} = s_2 \frac{1}{1 + \frac{2gh s_0 T_0}{V_t^2 s_2 T_J}} \quad (21)$$

from which

$$\frac{\Delta s_0 + \Delta s_2}{s_0 + s_2} = \frac{1}{1 + \frac{s_2}{s_0}} \left[\frac{1 - m^2}{1 + \frac{T_0}{T_J}} + \frac{1}{1 + \frac{2gh s_0 T_0}{V_t^2 s_2 T_J}} \frac{s_2}{s_0} \right] \quad (22)$$

From equations (12), (20), and (21),

$$w = W \left(\frac{EV_t}{2gr} \frac{1 - m}{1 + \frac{T_0}{T_J}} + \frac{h}{rV_2} \frac{1}{1 + \frac{2gh s_0 T_0}{V_t^2 s_2 T_J}} \right) \quad (23)$$

The weight of jet fuel for various reductions in the total take-off distance to clear a 50-foot obstacle is shown in figure 4(a) in percentages of the gross weight of the airplane and in pounds for an airplane weighing 42,000 pounds. The take-off velocity is 30 miles per hour. The ratio $s_0/s_2 = 2.6$ corresponds closely to the maximum performance of one present-day airplane. In figure 4(b), the weight of fuel is shown for a take-off velocity of 80 miles per hour and with $s_0/s_2 = 2.0$. Figure 4(c) shows the weight of fuel for a take-off velocity of 70 miles per hour and with $s_0/s_2 = 2.0$.

In the calculations, it was assumed that the take-off velocity, V_t , was equal to the mean flight velocity, V_2 .

Increase in take-off load by means of auxiliary jet propulsion. - Equations will now be derived for determining the increase in take-off load for a given total take-off distance obtainable by means of auxiliary jet propulsion. It will be assumed that the take-off occurs at the same lift coefficient as in the case of the normally loaded airplane.

Since the take-off velocity varies with the gross weight, the mean propeller thrust and the resistance must be determined under the new conditions. For the ground run, it is assumed that the mean values are those at $\sqrt{0.5} V_t$ as was assumed by Hartman (reference 12). The minimum resistance, R_0 , at this velocity with normal loading is given by (reference 12)

$$R_0 = \mu W + \frac{1}{2} V_t^2 \left(\frac{\rho}{2} f - \frac{\pi \rho}{8} \mu^2 b_e^2 \right) \quad (24)$$

where μ is the coefficient of rolling friction.

ρ mass density of the air.

f parasite area, square feet.

b_e effective span, feet.

If $\delta = (W + \Delta W)/W$ then, for the same lift coefficient at the take-off, the effective resistance with increased load during the ground run, $R_{0\delta}$ is given by

$$\begin{aligned} R_{0\delta} &= \mu W \delta + \frac{1}{2} V_t^2 \delta \left(\frac{\rho}{2} f - \frac{\pi \rho}{8} \mu^2 b_e^2 \right) \\ &= \delta R_0 \end{aligned}$$

The increased resistance, ΔR_0 is given by

$$\Delta R_0 = R_0 (\delta - 1) \quad (25)$$

The mean resistance in flight, R_2 , is given by

$$R_2 = \frac{\rho V_2^2}{2} f + \frac{2W^2}{\pi \rho V_2^2 b_e^2} \quad (26)$$

and, with added weight at the same lift coefficient, the resistance, $R_{2\delta}$, is given by

$$\begin{aligned} R_{2\delta} &= \frac{\rho V_2^2}{2} f \delta + \frac{2W^2 \delta^2}{\pi \rho V_2^2 \delta b_e^2} \\ &= \delta R_2 \end{aligned}$$

and the increase in resistance, ΔR_2 by

$$\Delta R_2 = R_2 (\delta - 1) \quad (27)$$

In order to determine the change in effective propeller thrust for the new take-off velocity, a knowledge of the propeller characteristics is necessary. As the increase in take-off distance with increased load is due primarily to the increase in weight and in the take-off velocity, it is unnecessary to determine the change in propeller thrust with much accuracy. The error introduced by completely disregarding the change in propeller thrust in the example to be given is only about 3 percent of the take-off distance with a 20-percent overload.

From equations (1) and (25), the increased ground run $s_{0\delta}$ is given by

$$\begin{aligned} s_{0\delta} &= \frac{V_t^2 \delta W \delta}{2G [T_0 + \Delta T_0 - R_0 (\delta - 1)]} \\ \text{or} \quad s_{0\delta} &= s_0 \delta^2 \frac{T_0}{T_0 + \Delta T_0 - R_0 (\delta - 1)} \end{aligned} \quad (28)$$

where ΔT_0 is the change in propeller thrust at $\sqrt{0.5} V_t$ as the weight is increased.

The increased flight distance, $s_{2\delta}$ to clear an obstacle is, from equations (10) and (27),

$$\begin{aligned} s_{2\delta} &= \frac{hW\delta}{T_2 + \Delta T_2 - R_2 (\delta - 1)} \\ \text{or} \quad s_{2\delta} &= s_2 \delta \frac{T_2}{T_2 + \Delta T_2 - R_2 (\delta - 1)} \end{aligned} \quad (29)$$

where ΔT_2 is the change in propeller thrust at V_2 .

With a constant added jet thrust, T_J , applied when the airplane reaches a velocity of $mV_t \delta^{1/2}$ the reduced ground run $s_{0\delta}'$ is, from the equations (10) and (28),

$$s_{0\delta'} = s_0 \delta^2 \frac{T_0}{T_0 + \Delta T_0 - R_0 (\delta - 1)} \left[1 - \frac{(1-m^2)T_J}{T_0 + \Delta T_0 - R_0 (\delta - 1) + T_J} \right] \quad (30)$$

From equations (16), (18), and (29), the reduced flight distance, $s_{2\delta'}$, to clear an obstacle of height h with constant added jet thrust is given by

$$s_{2\delta'} = s_2 \delta^2 \frac{T_2}{T_2 + \Delta T_2 - R_2 (\delta - 1) + T_J} \quad (31)$$

The values of m and T_J are then found from equations (30) and (31) so that

$$s_{0\delta'} + s_{2\delta'} = s_0 + s_2$$

From equation (12), the weight of fuel, w_0 , used during the ground run is given by

$$w_0 = \frac{KV_t W (1 - m) T_J \delta^{3/2}}{2gr [T_0 + \Delta T_0 - R_0 (\delta - 1) + T_J]} \quad (32)$$

and, from equations (15), (16), and (20), the weight of fuel, w_2 , used during the flight to clear an obstacle is given by

$$w_2 = \frac{hW \delta^{1/2}}{rV_t} \frac{T_J}{T_2 + \Delta T_2 - R_2 (\delta - 1) + T_J} \quad (33)$$

As an example, the calculations were carried out for the same airplane that was used for the construction of figure 4; the additional assumptions were made that

$$\mu = 0.05$$

$$b_e^2 = 10,350 \text{ square feet.}$$

$$f = 42 \text{ square feet (for take-off).}$$

Maximum velocity at the take-off power rating =
258 miles per hour.

Maximum propeller efficiency = 84 percent.

Take-off power rating = 4,400 brake horsepower.

$$s_0 = 1,040 \text{ feet.}$$

$$s_2 = 400 \text{ feet.}$$

The changes in propeller thrust, ΔT_0 and ΔT_2 , were calculated from the data of figure 7 of reference 12, which gives the thrust horsepower in terms of velocity and thrust horsepower at maximum velocity.

Figure 5 shows the increase in complete take-off distance when additional gross weight is added. The values of m and T_J necessary to reduce this distance to the original take-off distance at normal load are given in figure 6; figure 7 shows the weight of gasoline and oxygen that must be used in a jet to provide the required thrust. In figure 8, the ratio $w/\Delta W$ is plotted against m . The curve shown is an average for four values of δ .

Comparison of auxiliary jet propulsion with an internal-combustion engine and a propeller as a take-off aid. - In order to decide whether any advantage is to be gained by the use of auxiliary jet propulsion, it is necessary to determine the weight of an internal-combustion engine and a propeller that will produce the same result.

For the simplification of the calculations, it will be assumed that the propeller diameter is proportional to the take-off power and that the propeller is operated at the original V/nD where V is the forward velocity; n , the propeller revolution speed; and D , the propeller diameter. These conditions make the net thrust proportional to the power. It will also be assumed that the dry-engine weight is 1.25 pounds per take-off horsepower and that the weight of the propeller and accessories is 0.35 pound per take-off horsepower.

The additional weight of the internal-combustion engine that will provide a given increase in thrust, T_J/T_0 is then

$$\Delta W_e = W_e \frac{T_J}{T_0 + R} = W_e \frac{T_J}{T_0} \frac{1}{1 + R/T_0}$$

where W_e is the weight of the engine and propeller. Substituting from equation (1) for T_0

$$\frac{\Delta W_e}{W_e} = \frac{T_J}{T_0} \frac{1}{1 + \frac{2gs_0R}{V_t^2 W}}$$

and, substituting $1.6P$ for W_e

$$\frac{\Delta W_e}{W} = \frac{T_J}{T_O} \frac{1.6}{\frac{W}{P} \left(1 + \frac{2g s_O R}{V_t^2 W} \right)} \quad (34)$$

where P is the engine brake horsepower. The resistance, R is the minimum resistance determined at $\sqrt{0.5} V_t$. For approximate computations, it is convenient to assume that

$$R = \mu W$$

which gives

$$\frac{\Delta W_e}{W} = \frac{T_J}{T_O} \frac{1.6}{\frac{W}{P} \left(1 + \frac{2g s_O \mu}{V_t^2} \right)} \quad (35)$$

The reduction in ground run for an increase in thrust of T_J is the same as that obtained with a jet for $m = 0$ (equation (10)). The ratio

$$\frac{\Delta W_e / T_J}{W / T_O}$$

is plotted in figure 9 for take-off velocities of 70 and 80 miles per hour and for ground runs of 500, 1,000, 2,000, and 3,000 feet for $\mu = 0.05$. In the event that R is greatly different from

μW the value of $\frac{\Delta W_e / T_J}{W / T_O}$ may be found from equation (34).

In the case for which the jet was used, the reduction of the take-off distance was calculated on the assumption that the jet thrust, T_J , was constant throughout both the ground run and the air-borne portion of the take-off. When an engine and a propeller are used, however, the mean additional thrust is lower during the air-borne portion of the take-off than during the ground run. It is therefore necessary, in order to obtain the same reduction in the complete take-off distance, to provide an engine that will give a thrust, T , at a velocity $\sqrt{0.5} V_t$, which is somewhat greater than the jet thrust, T_J .

Let
$$\Delta = \frac{T}{T_O} - \frac{T_J}{T_O}$$

If the ratio of the propeller thrust at the velocity V_2 to the propeller thrust at the velocity $\sqrt{0.5} V_t$ is K_1 the same reduction in complete take-off distance is achieved when, from equation (22),

$$\frac{T_J/T_O}{1 + \frac{T_J}{T_O}} + \frac{T_J/T_O}{\frac{T_J}{T_O} + \frac{2ghs_O}{V_t^2 s_2}} \frac{s_2}{s_O} = \frac{\Delta + T_J/T_O}{\Delta + \frac{T_J}{T_O} + 1} + \frac{\Delta + T_J/T_O}{\Delta + \frac{T_J}{T_O} + \frac{2ghs_O}{K_1 V_t^2 s_2}} \frac{s_2}{s_O} \quad (36)$$

Expanding the right-hand side in a power series, neglecting all terms above the first order in Δ and solving for $\frac{\Delta}{T_J/T_O}$ gives

$$\frac{\Delta}{T_J/T_O} = \frac{2gh}{V_t^2} \frac{1-K_1}{K_1} \frac{\frac{T_J}{T_O} + \frac{2ghs_O}{K_1 V_t^2 s_2}}{\frac{T_J}{T_O} + \frac{2ghs_O}{V_t^2 s_2}} \left[\frac{(T_J/T_O + 1)^2}{\left(\frac{T_J}{T_O} + \frac{2ghs_O}{K_1 V_t^2 s_2} \right)^2 + \frac{2gh}{K_1 V_t^2} \left(\frac{T_J}{T_O} + 1 \right)^2} \right] \quad (37)$$

The value of $\frac{\Delta}{T_J/T_O}$ is plotted in figure 10 for several take-off conditions. Since propeller thrust was assumed to be proportional to power and power to weight, the factor $\frac{\Delta}{T_J/T_O}$ represents the fractional increase in engine and propeller weight that is due to the reduction of thrust with increasing air speed.

The additional weight of engine and propeller required for a given reduction of the take-off run is shown in figure 11, for the airplane of figure 5, together with the weight of jet fuel required for the same conditions for $m = 0$ and 0.5.

For the condition in which the gross weight of the airplane was increased, the increased weight of engine and propeller required to maintain the same total take-off distance was calculated directly for the special case of figure 7. The weight of engine and propeller required is shown in figure 12 together with the weight of jet fuel required for $m = 0$ and 0.5.

The weight of the complete jet motor and fuel tanks is difficult to predict. The weight of the fuel tanks will depend upon the weight of fuel to be burned and the operating pressure of the tanks. The weight of combustion chamber, nozzle, and necessary fuel pumps will depend upon the rate of fuel consumption and cannot be estimated. Goddard (reference 14), however, built a jet motor, using no fuel pump, which weighed 5 pounds and produced a thrust of 289 pounds.

Inasmuch as the exact weight of equipment required for the use of auxiliary jet propulsion cannot be fixed, it is possible to determine only the limiting values for this weight above which auxiliary jet propulsion would be definitely impracticable. Approximate values of the maximum permissible equipment weight may be determined from figures 11 and 12.

DISCUSSION OF RESULTS

Table I shows the results of a few experiments with jet motors reported in references 14 to 17 together with the specific fuel and oxidant consumption and the relative fuel consumption as compared with an internal-combustion engine and propeller. The limiting or ideal reactions have been calculated from tables in reference 17.

In the examples given in the present report, the experimental reactions of fuels 1 to 4 in table I have been used. The reactions reported for gunpowder were for single explosions of small masses of powder; the reactions for liquid fuels were for continuous jet-motor operation. The available energy of gunpowder is lower than that of liquid fuels. As the powder-using motors operated at much higher pressures than the liquid-using motors, the higher efficiency of the thermodynamic cycle more than offset the lower heat content. Goddard, who conducted the experiments with gunpowder, found it expedient to use liquid fuels in his experiments with rocket flight because of the convenience in operation and the lighter weight of auxiliary equipment. For this same reason, the reactions of liquid fuels were used in most of the charts presented herein. The lower values for gasoline-oxygen and alcohol-oxygen were used because no data concerning test procedure were given in reference 16, from which the higher values were taken. It is probable that the efficiency of liquid-fuel jet motors could be improved by operating at higher pressures and by improving nozzle design.

The weight of jet fuel required to reduce the ground run of an airplane by the amount $\Delta s_0/s_0$ is shown in figure 1. The weight of fuel required for a given fractional reduction of ground run is proportional to the take-off velocity and is independent of the length of the ground run.

Figure 2(a) shows the comparative effectiveness of starting the jet at various airplane velocities, mV_t , during the ground run for a take-off velocity of 70 miles per hour. The weights of gasoline and oxygen required for various values of m and the contours of constant jet thrust are plotted against the reduction of the ground run. Following these contours shows that a considerable saving in the weight of fuel required could be realized by delaying the operation of the jet. For example, for the 4,200-pound airplane when $m = 0$ and $T_j/T_0 = 0.4$, the weight of fuel required is 23.2 pounds for a reduction in the ground run of 28.5 percent. If the jet thrust is doubled ($T_j/T_0 = 0.8$), m is about 0.6 and the weight of fuel required for the same reduction of the ground run is reduced to 15.1 pounds, a saving of about 35 percent. The same quantities are plotted in figure 2(b) as in figure 2(a) for a take-off velocity of 80 miles per hour. The weight required for a given fractional reduction of the ground run is proportional to the take-off velocity.

The weights of four fuels (fuels 1 to 4, table I) required to reduce the distance flown during the initial climb to an altitude of 50 feet are given in figure 3(a) in percentages of the gross weight of the airplane and for two airplanes whose gross weights are 4,200 and 42,000 pounds for a take-off velocity of 70 miles per hour. A comparison of figure 3 with figure 2 shows that auxiliary jet propulsion is more effective in flight than on the ground. For example, for the 4,200-pound airplane, a reduction of 10 percent of the ground run requires 8.4 pounds of gasoline and oxygen when $m = 0$ and requires 5.6 pounds when $m = 0.5$ but, for a 10-percent reduction in the flight distance, the weight required is only 1.3 pounds. The reason for this reduction is that the energy required for the acceleration to take-off velocity is much greater than the energy required for the climb to a 50-foot altitude. Figure 3(b) is similar to figure 3(a) except that the take-off velocity is 80 miles per hour. The weight of fuel required for a given fractional reduction of the air-borne distance is inversely proportional to the take-off velocity.

The weight of gasoline and oxygen required to reduce the total take-off distance to clear a 50-foot obstacle is given in figure 4(a) in percentages of the airplane gross weight and in pounds for an airplane gross weight of 42,000 pounds. The assumed value of s_0/s_2 was 2.6 and, of the take-off velocity, was 80 miles per hour. In order to demonstrate the effect of changes in these important parameters, figures 4(b) and 4(c) were plotted, for which the value of s_0/s_2 was assumed to be 2.0 and, of the take-off velocities, to be 80 and 70 miles per hour, respectively.

It may be seen from figure 4(a) that, even when $s_0 = 2.6s_2$, auxiliary jet propulsion is more effective in flight than on the ground. The normal excess thrust being greater on the ground than in the initial climb, the jet will always be more effective in the initial climb than on the ground.

The additional reduction in take-off distance to be gained by operating the jet at low values of m is negligible, as is apparent from the lines of constant T_J/T_0 . For example, for $T_J/T_0 = 0.3$, the maximum reduction in the take-off distance is 25.8 percent for $m = 0$, which requires 260 pounds of fuel. If m is increased to 0.2, the reduction in the take-off distance is 25.1 percent, a slight sacrifice in take-off performance, but the fuel consumption is reduced to 215 pounds, a saving of 17.3 percent.

A comparison of figures 4(a) and 4(b) shows the effect of variation of the division of the take-off distance between the ground run and the flight path. As is to be expected, auxiliary jet propulsion is more effective in producing a given fractional reduction of the take-off distance when a greater part of that distance is air-borne (fig. 4(b)).

A comparison of figures 4(b) and 4(c) shows the effect of variation of the take-off velocity on the effectiveness of auxiliary jet propulsion. In the discussion of figure 2, it was pointed out that the weight of fuel required for a given reduction of the ground run is proportional to the take-off velocity and, in the discussion of figure 3, that the weight of fuel required for a given reduction of the flight distance is inversely proportional to the take-off velocity. Similarly, in the present case, the weight of fuel required for a given fractional reduction of the take-off distance is greater for large values of m and smaller for small values of m when the take-off velocity is 70 miles per hour than it is when the take-off velocity is 80 miles per hour.

Figure 5 shows the increase in the total take-off distance to clear a 50-foot obstacle with an increase in gross weight for the same airplane that was used for figure 4 with the additional characteristics described in the analysis.

The additional thrust required to reduce this increased take-off distance to that of the normally loaded airplane is given in figure 6 as a function of the parameters m and δ . Figure 7 shows the weight of gasoline and oxygen required for this reduction for various values of δ , m , and T_J .

The weight of fuel required in percentage of the increase in gross weight is shown in figure 8 as a function of m . The single curve is a mean for four values of δ , the percentage of weight required being practically independent of δ . It may be seen that, for $m = 0.5$, the additional weight which may be carried for the same take-off distance increases 27 times as fast as the weight of jet fuel required. As the value of m is increased, the weight of jet fuel required decreases but only at the expense of increasing the jet thrust.

In figures 11 and 12, the weight of jet fuel is compared with the weight of an internal-combustion engine and a propeller. The ratio of the weight of engine and propeller to the weight of jet fuel is 8 for $m = 0$ and 11 for $m = 0.5$ for the conditions of figure 11; the ratios are 5.5 for $m = 0$ and 8 for $m = 0.5$ for the conditions of figure 12.

The power loading was considered to be low in the previous examples in which the weight of fuel was compared with the weight of the engine and propeller required for the same improvement in take-off performance. The ratio of the weight of engine and propeller to the weight of jet fuel may be considerably less for high power loadings. Let it be assumed that an airplane having a gross weight of 42,000 pounds and a power loading of 24 pounds per brake horsepower requires 3,000 feet for the ground run to take off at 70 miles per hour. In order to reduce this distance to 1,500 feet, an added thrust given by T_J/T_0 equal to 1 is required. From equation (35), the weight of the engine and propeller required is 1,470 pounds. For the same reduction of the ground run by means of auxiliary jet propulsion, the weight of gasoline and oxygen required for $m = 0$ is 420 pounds and, for $m = 0.5$, is 280 pounds.

Because auxiliary jet propulsion was found to be more effective during the air-borne portion of the take-off than during the ground run, it is interesting to see how the engine and propeller compare with auxiliary jet propulsion at this power loading when used during the air-borne portion of the take-off as well as during the ground run. If it is assumed that $s_0/s_1 = 2.0$, then, from equation (22) for a value of T_J/T_0 of 1, the reduction of the complete take-off distance is 54 percent. From figure 10, the weight of the additional engine and propeller to accomplish this reduction of the take-off distance must be increased to 1,520 pounds if $K_1 = 0.9$ and to 1,575 pounds if $K_1 = 0.8$. Equations (22) and (23) give the total weight of jet fuel required for the same performance as 460 pounds for $m = 0$ and as 325 pounds for $m = 0.5$.

The weight of engine and propeller is seen to be not less than 3.5 times the weight of fuel required by the jet-propulsion device even for high power loadings. For low power loadings, the ratio is higher. In order to complete the comparison, the weight of the jet-propulsion device and its fuel tanks is required. Africano in reference 17 estimates, for a rocket carrying 31 pounds of fuel, that the dead weight of the device can safely be limited to 0.64 times the weight of the fuel. Even if this ratio for a higher weight of fuel should be increased by several hundred percent, the advantage, from weight considerations, is still in favor of auxiliary jet propulsion.

It is possible that a jet motor could be discarded after the take-off because it would have no further function; no comparison with an internal-combustion engine is then necessary. In any event, the weight of fuel will not diminish the pay load because the fuel will all be consumed by the time the take-off is completed.

Experiments conducted by the several investigators (references 14 to 17) show that the thrust per pound of fluid per second can be appreciably improved by further development. The weight of jet fuel can therefore be correspondingly reduced. The foregoing discussion indicates that serious consideration should be given to auxiliary jet propulsion as a take-off aid.

CONCLUSIONS

The conclusions drawn from the preceding analysis and from the experimental work of other investigators are:

1. The weight of jet fuel required for a given improvement in the take-off is sufficiently small as compared with the additional weight of the larger engine and propeller required for the same improvement to indicate that auxiliary jet propulsion is a promising means of aiding the take-off. The weight of necessary equipment should be small.
2. The weight of jet fuel required to maintain a given total take-off distance as the gross weight of the airplane is increased is small as compared with the increase in gross weight.
3. Auxiliary jet propulsion would be most effective as a take-off aid when used late in the ground run and in the airborne portion of the take-off.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 26, 1939.

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TABLE I
RESULTS OF EXPERIMENTS ON JET PROPULSION

Fuel	Fuel and oxidant	Jet velocity (f p s)	Thrust/gas flow (lb /lb /sec)		Approximate thermal efficiency (percent)	Specific jet power (hp /lb /sec)	Specific fuel consumption (lb /jet hp-hr)	At V = 100 f p s		At V = 300 m p h		Reference
			Experi-mental	Ideal				Propulsive efficiency (percent)	Relative fuel consumption	Propulsive efficiency (percent)	Relative fuel consumption	
1	Gunpowder No 1	7,990	248	328	58	1,802	2.0	2.5	72	11	31	14
2	Gunpowder No 2	5,340	165.8	292	33	805	4.5	3.75	108	17	46	14
3	Gasoline and oxygen	5,000	155.3	453	12	706	5.1	4.0	111	18	49	15
4	Alcohol and oxygen	3,700	115	426	7.3	387	9.3	5.4	155	24	67	17
5	Gasoline and oxygen	6,890	214	453	22	1,340	2.7	2.9	83	13	36	16
6	Alcohol and oxygen	7,220	224	426	28	1,472	2.5	2.8	80	12	34	16
7	Hydrogen and oxygen	13,780	428	527	66	5,361	0.67	1.45	42	6.4	18	16
8	Internal combustion engine and propeller	---	---	---	27	^a 7,200	^b 0.5	45.0	1	85.0	1	--

^ab hp /lb /sec^blb /b hp-hr

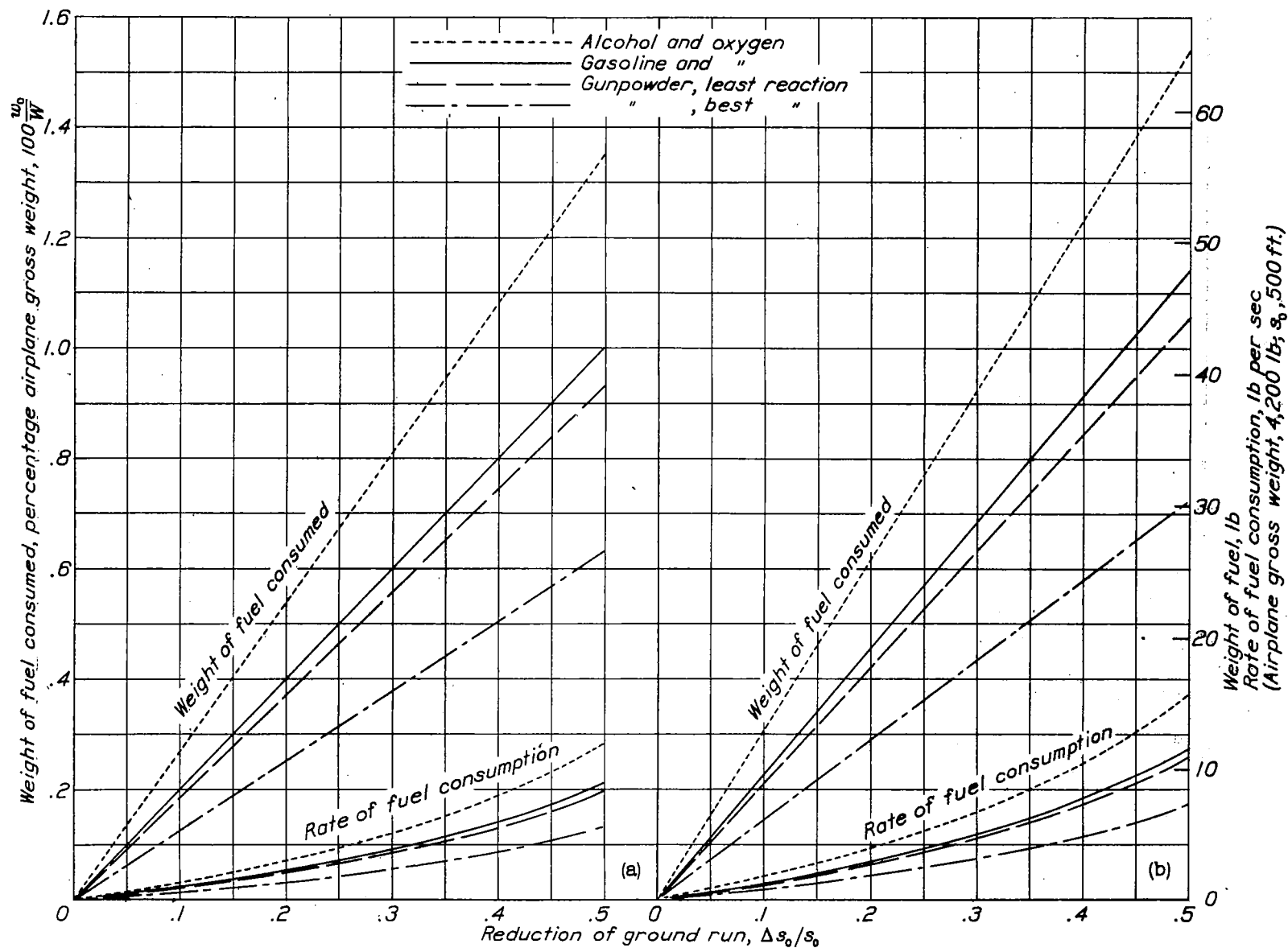
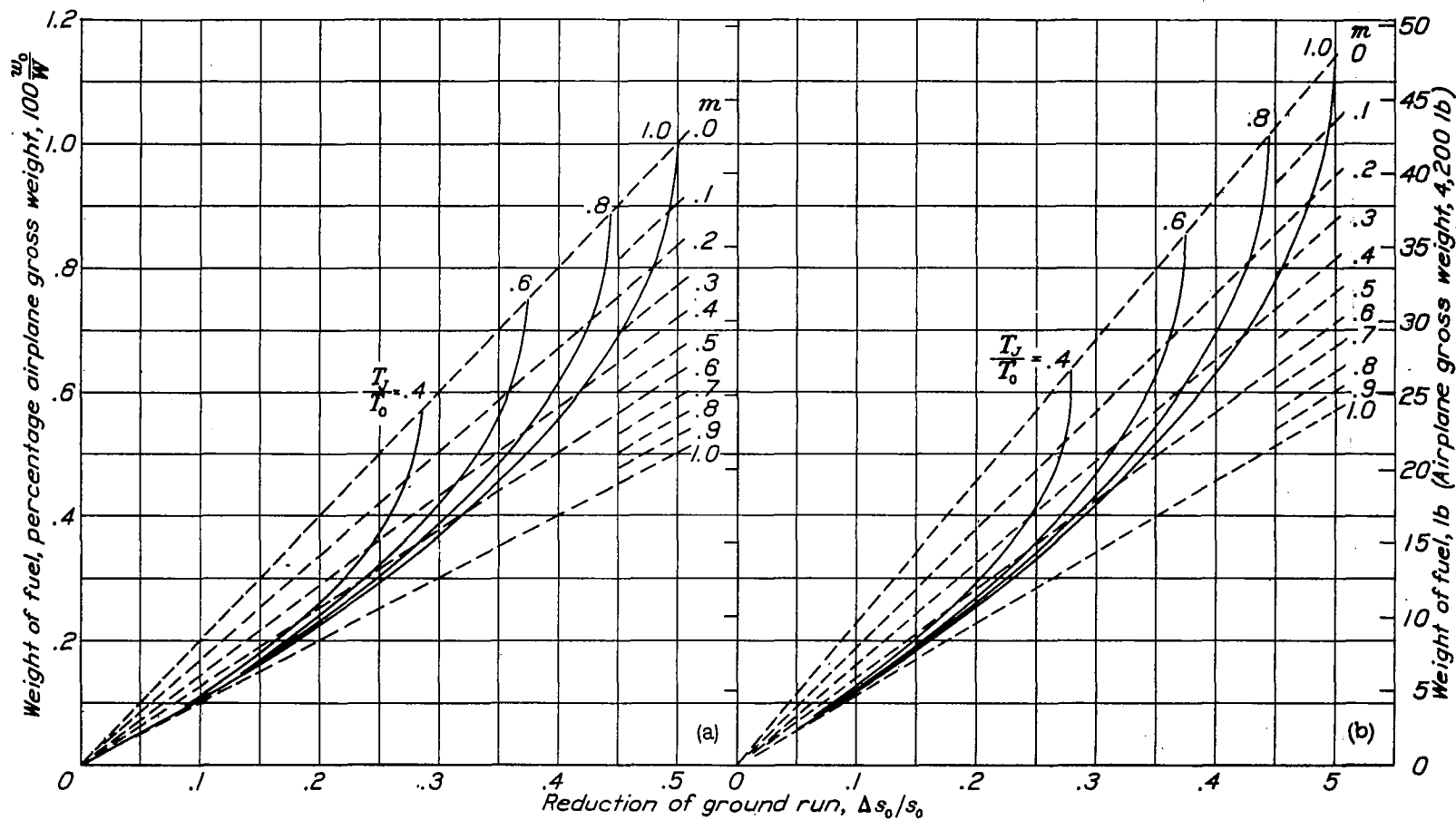


Fig. 1

N.A.C.A.

Figure 1.- Fuel required to reduce ground run by means of auxiliary jet propulsion.



(a) Take-off velocity, 70 miles per hour.

(b) Take-off velocity, 80 miles per hour.

Figure 2.- Weight of fuel (gasoline and oxygen) required to reduce ground run for various values of the parameter m .

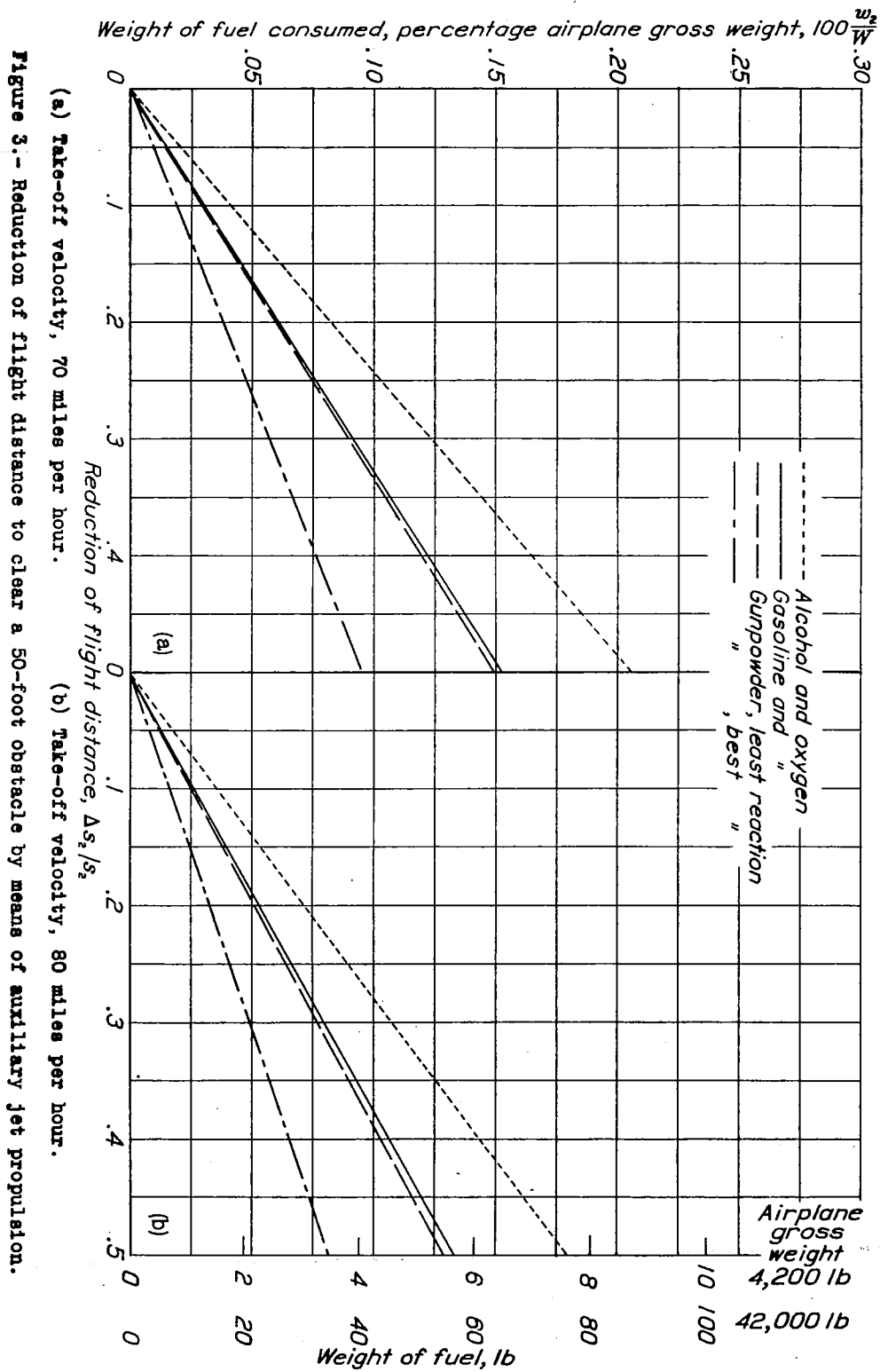


Fig. 3

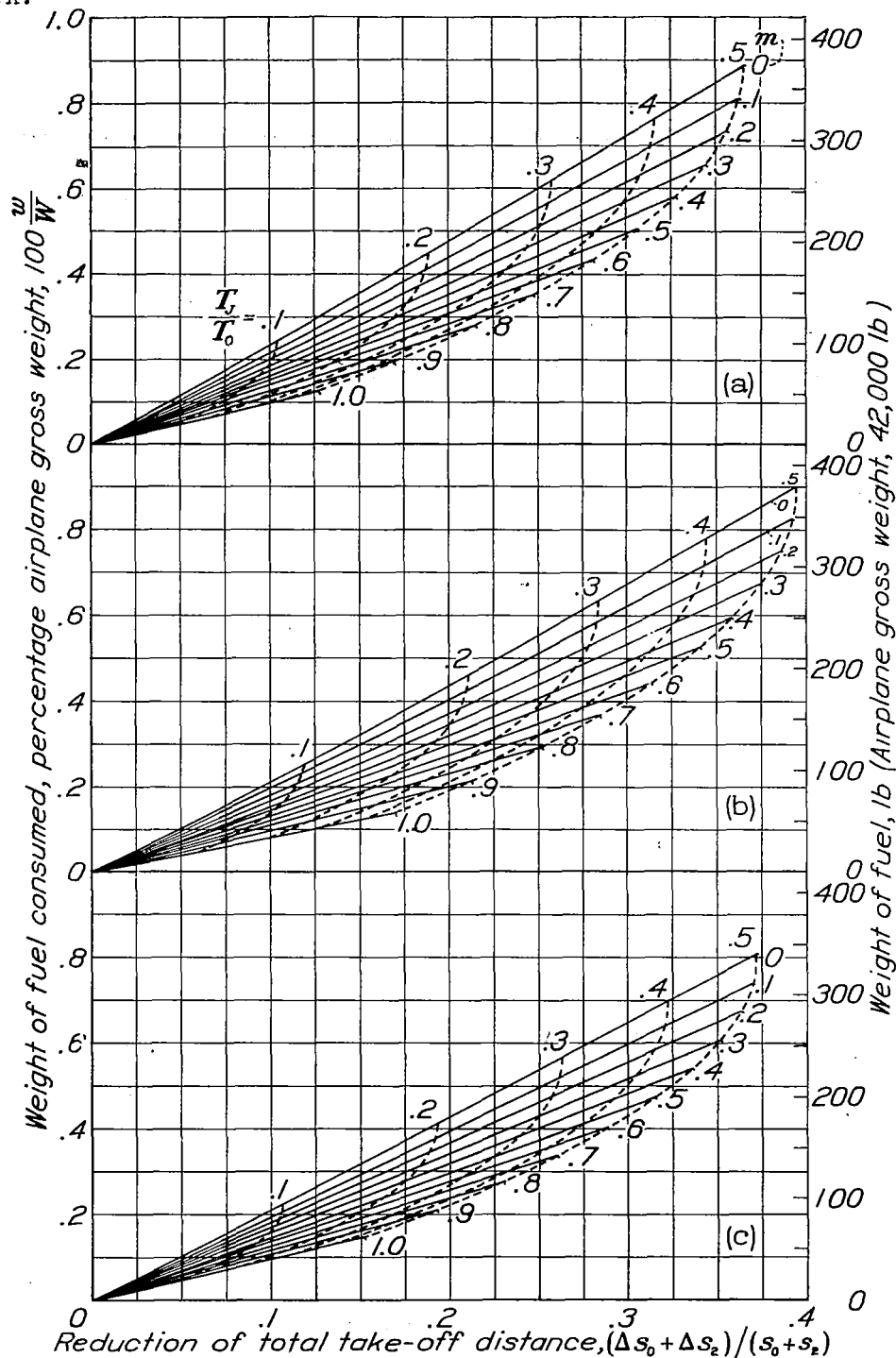


Figure 4.- Weight of fuel (gasoline and oxygen) required to reduce total take-off distance to clear a 50-foot obstacle by means of auxiliary jet propulsion.

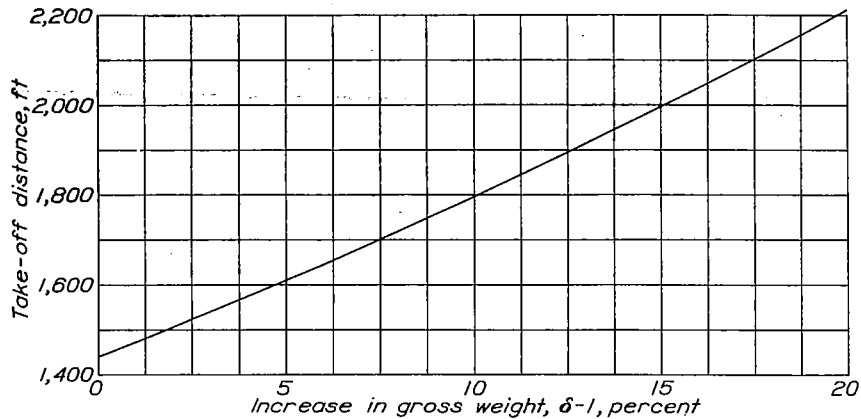


Figure 5.- Increase in total take-off distance to clear 50-foot obstacle with increase in gross weight.

s_o , 1,040 feet; s_2 , 400 feet; W , 42,000 pounds; V_t , 80 miles per hour; V_{max} , 258 miles per hour; take-off power, 4,400 brake horse power; b_e^2 , 10,350 square feet; f , .42 square feet.

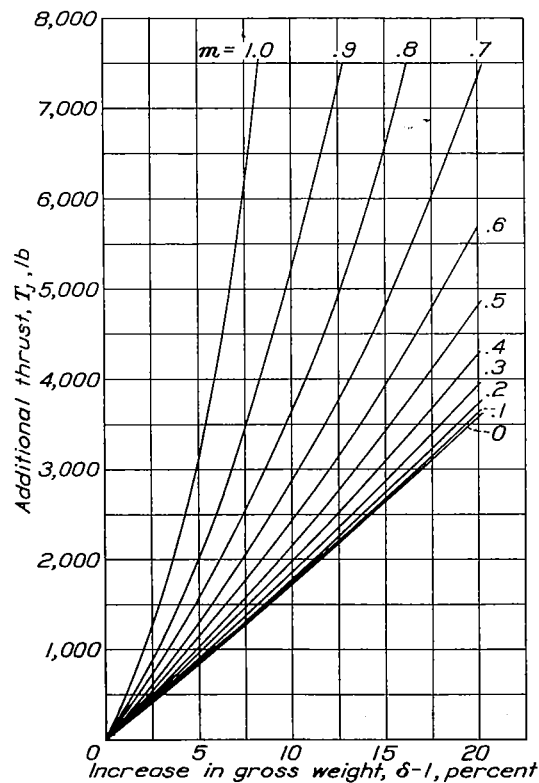


Figure 6.- Additional thrust required to obtain normal take-off distance when gross weight is increased. Airplane of figure 5.

Figure 7.- Weight of fuel (gasoline and oxygen) required to maintain normal total take-off distance over a 50-foot obstacle as gross weight is increased. Airplane of figure 5.

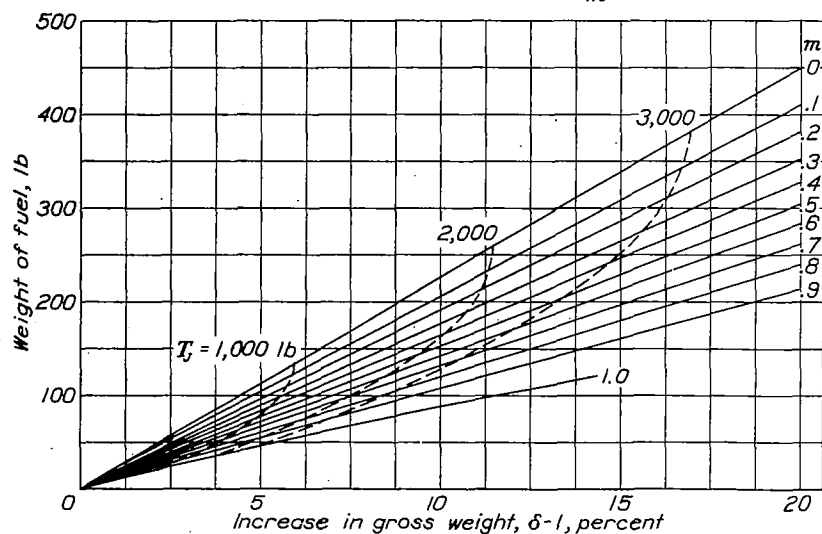
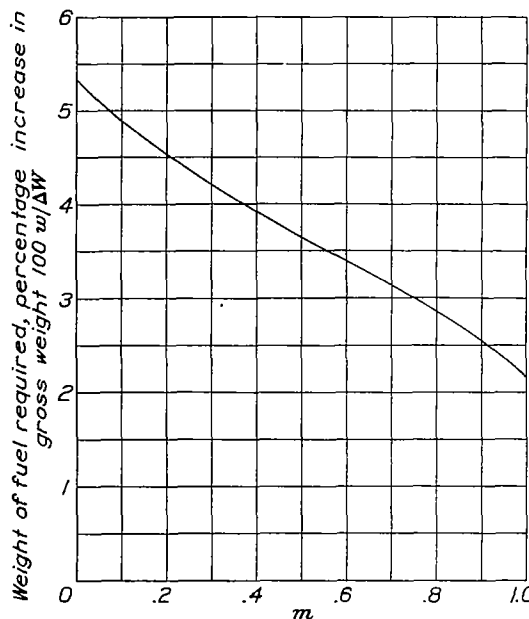


Figure 8.- Weight of fuel (gasoline and oxygen) expressed in percentage of the increase in gross weight, required to maintain normal total take-off distance to clear a 50-foot obstacle by means of auxiliary jet propulsion. Airplane of figure 5.

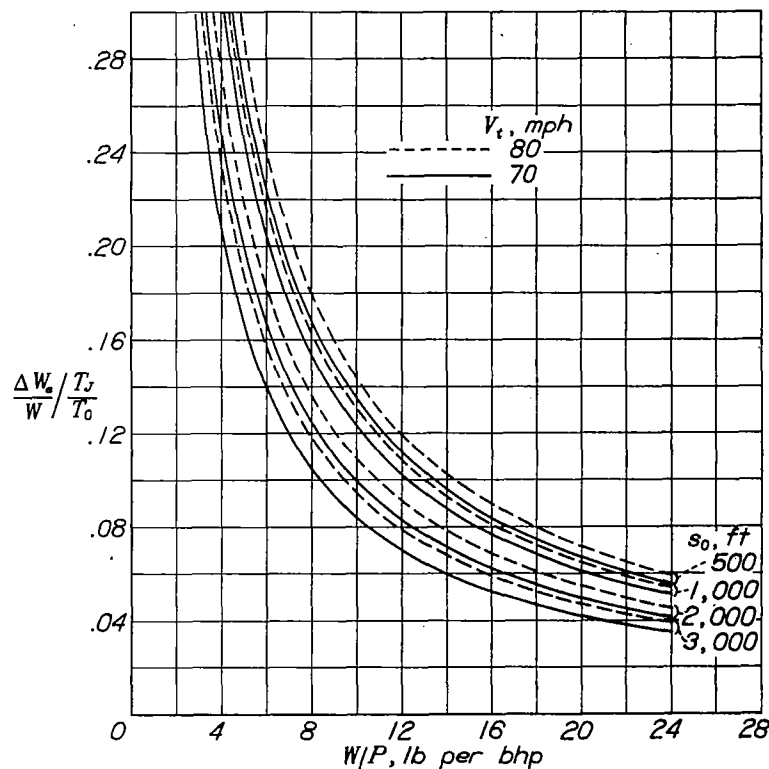


Figure 9.- Weight of engine and propeller required to increase the effective excess thrust during the ground run. $\mu, 0.05$

Figure 11.- Comparison of weight of jet fuel (gasoline and oxygen) with weight of an internal-combustion engine and a propeller for reduction of the total take-off distance. Airplane of figure 5.

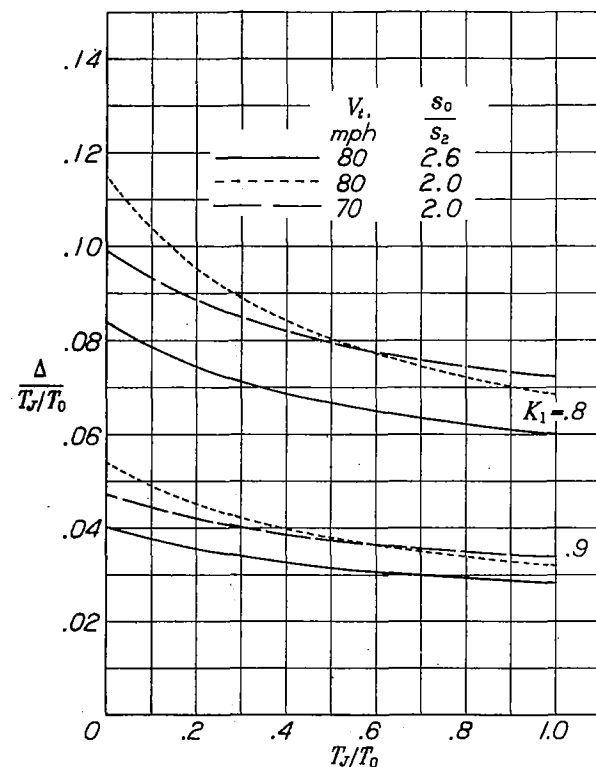
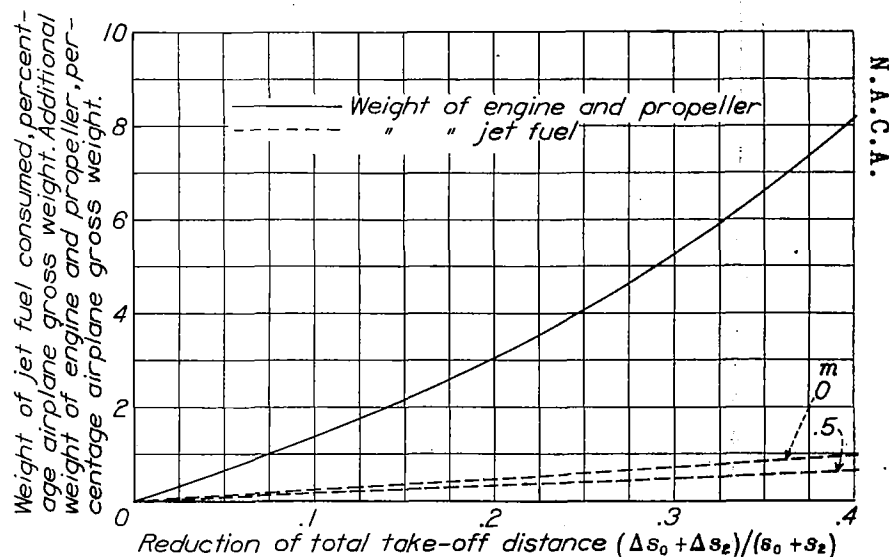
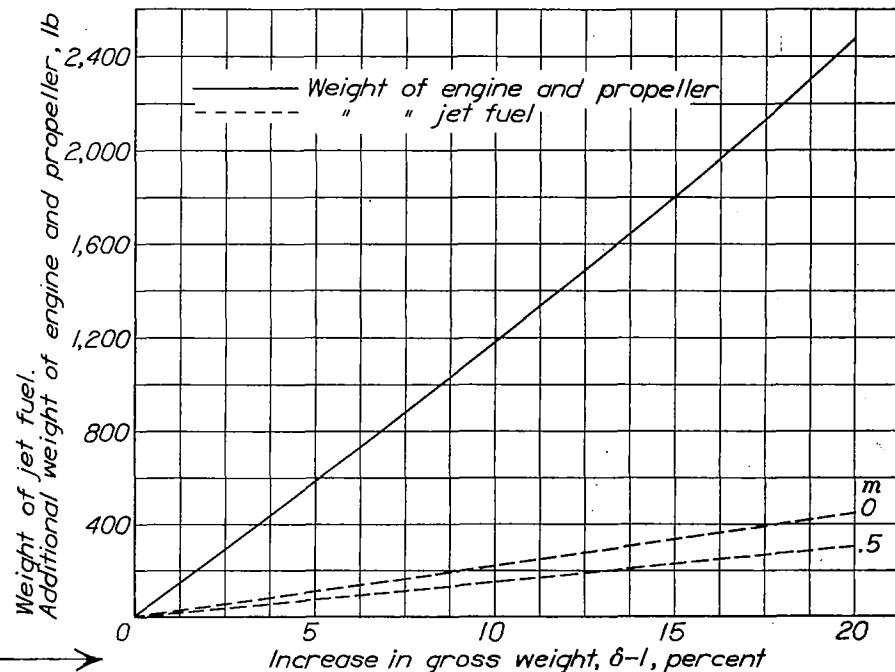


Figure 10.- Additional thrust required for reduction of total take-off distance with an internal-combustion engine and a propeller.

Figure 12.- Comparison of weight requirements of auxiliary jet propulsion with an internal-combustion engine and a propeller for increase of gross weight.



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